

Heat Pipe Activity in the Americas - 1990 to 1995

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Abstract

Development activity in heat pipe and thermosyphon technology in the Americas from January 1990 through December 1995 is surveyed. This period was selected because of the lack of a regional report for the Americas at the 8th International Heat Pipe Conference and the high level of activity since 1990. Heat pipe related journal articles and conference papers as well as books by American authors are cited. This report is by no means comprehensive. Only representative citations are given, as their vast number from various sources make selection in every report section mandatory. Because coverage of a six year period is attempted, a bibliographic form was selected rather than the more customary summary form. Mention is also made of some products developed by commercial heat pipe manufacturers in the US and Canada who do not normally publish their work.

Introduction

During this period a number of conferences were devoted in whole or in part to various aspects of heat pipe research and development. The 7th International Heat Pipe Conference was held on May 21-25, 1990 in Moscow, USSR where 14 papers were presented by authors residing in the US, Canada, and Cuba. Topics covered by these authors included two-phase thermosyphons; solar energy applications; hypersonic vehicle cooling; vapor flow modeling; gas-controlled, rotating, and micro heat pipes; and heat pipe transient analysis. Conference proceedings were published by CRC Press in two volumes (Vasiliev, 1993).

The 8th International Heat Pipe Conference was held on September 14-18, 1992 in Beijing, China. A number of conference papers were produced by American authors: 16 papers from the US, three papers from Brazil, and one paper by a Canadian author. The topics of papers presented by American authors at the Beijing conference included heat pipe numerical analysis, low power liquid metal heat pipe operation, heat pipe thermal energy storage, binary mixture pool boiling, heat pipe transient response, liquid metal frozen startup, two fluid thermosyphons, diffusion in gas-loaded heat pipes, body force effects on heat pipe operation, micro heat pipes, corrosion in heat pipes, and heat pipes applied to solar energy and to particle accelerator thermal control. Conference proceedings are available from International Academic Publishers (Tongze, 1993).

The 9th International Heat Pipe Conference was held in Albuquerque, New Mexico on May 1-5, 1995. Over 75 American authors contributed papers to the Albuquerque conference proceedings of which this report is a part.

Three volumes of compiled papers devoted exclusively to heat pipe technology were published by the ASME Heat Transfer Division during this period. *Heat Pipes and Thermosyphons* contains five papers on heat pipe and thermosyphon fundamentals and an additional three papers on heat pipe applications (Chang, 1992). Papers in this volume were presented at the 1992 ASME Winter Annual Meeting held on November 8-12, 1992 in Anaheim, California. *Heat Pipes and Capillary Pumped Loops* contains two papers on capillary pumped loops, three papers on micro heat pipes and an additional five papers covering other area Faghri (1993b). These papers were presented at the 29th National Heat Transfer Conference held on August 8-11, 1992 in Atlanta, Georgia. *Fundamentals of Heat Pipes* includes several papers on thermosyphons, and papers covering flat, gas-loaded, micro, and artery heat pipes (Chang, 1994). These papers were presented at the 6th AIAA/ASME Thermophysics and Heat Transfer Conference held on June 20-23, 1994 in Colorado Springs, Colorado.

Several books covering heat pipe technology were published by American authors during this period. C. C. Silverstein (1992) at CCS Associates in Bethel Park, Pennsylvania, authored the book: *Design and Technology of Heat Pipes for Cooling and Heat Exchange* which gives a classical description of heat pipe physics and design methods. The vast majority of the references cited in the book date from the 1960s and 1970s. Topics covered include heat pipe operating characteristics, fluid flow in capillary structures, heat transport limits, as well as steady-state and transient heat pipe behavior. Silverstein also presents several illustrative design examples. G. P. Peterson (1994) at Texas A&M wrote a general heat pipe textbook: *An Introduction to Heat Pipes: Modeling, Testing, and Applications*. Peterson's book includes sections on basic phenomena in heat pipes and thermosyphons, heat pipe operating limits and performance modeling, an extensive section on micro and rotating heat pipes, design and manufacturing considerations, and heat pipe applications in the electronics industry. A. Faghri (1995) at the University of Connecticut produced a 874 page tome: *Heat Pipe Science and Technology*. Faghri gives a detailed treatment of a broad range of heat pipe-related topics including: continuum transient and frozen startup behavior of heat pipes, variable conductance heat pipes, two-phase closed thermosyphons, micro and miniature heat pipe characteristics and operating limits, capillary pumped loops, and heat pipe heat exchangers.

Citations of selected US Patents in heat pipe technology are available in bibliographic form from the US Department of Commerce, National Technical Information Service, Published Search[®] database. The US patents contained in this database are granted to both US and foreign nationals. A search of this database from 1990 through 1994 revealed 93 citations related to heat pipe technology.

A list of categories used in this report is shown in Table 1. The categories selected tend to reflect the application-oriented nature of heat pipe development. Some natural overlap does occur between categories: an article included in one category might also appear in

other categories as well. Table 2 lists some of the journals that have published heat pipe-related work by authors residing in the Americas during the 1990 to 1995 period.

Table 1. Categories used in this report in order of appearance.

Category Number	Category Type	Category
1	Application	Aircraft Temperature Control using Heat Pipes
2	Application	Electronic Cooling Heat Pipes
3	Application	Heat Pipes in Heat Exchangers and Industrial Processes
4	Application	Solar Energy Conversion using Heat Pipes
5	Application	Spacecraft Heat Pipe Development
6	Basic Study	Heat Pipe Modeling
7	Basic Study	Heat Pipe Performance Limits
8	Basic Study	Material Issues Related to Heat Pipes
9	Function	Capillary Pumped Loops
10	Function	Gas Loaded and Variable Conductance Heat Pipes
11	Function	Micro and Miniature Heat Pipes
12	Function	Rotating Heat Pipes and Thermosyphons
13	Function	Thermosyphon Heat Pipes
14	Temperature Range	Low Temperature and Cryogenic Heat Pipes
15	Temperature Range	Alkali Metal Heat Pipes (Experimental)

Table 2. Some Journals that Have Published Heat Pipe Related Work by American Authors During 1990-1995.

Acta Optica Sinica
 Advances in Cryogenic Engineering
 AIChE Journal
 ASHRAE Transactions
 Cold Regions Science and Technology
 Computational Mechanics
 Cryogenics
 Energy
 Energy Conversion and Management
 Heat and Technology
 Heat Recovery Systems and CHP
 Heat Transfer Engineering
 Heat Transfer Research
 International Communications in Heat and Mass Transfer
 International Journal of Energy Research
 International Journal of Heat and Fluid Flow
 International Journal of Heat and Mass Transfer
 International Journal of Machine Tools and Manufacture
 International Journal of Thermophysics
 Journal of Electromechanical Systems
 Journal of Electronic Packaging
 Journal of Engineering Materials and Technology
 Journal of Enhanced Heat Transfer
 Journal of Heat Transfer
 Journal of Medical Engineering and Technology
 Journal of Propulsion and Power
 Journal of Solar Energy Engineering
 Journal of Spacecraft and Rockets
 Journal of Thermophysics and Heat Transfer
 Mathematical and Computer Modeling
 Numerical Heat Transfer. Part A, Applications.
 Numerical Heat Transfer. Part B, Fundamentals.
 Optical Engineering
 Renewable Energy
 S T L E Tribology Transactions
 SAE Journal
 Solar Energy
 Space Power
 Space Power Resources, Manufacturing and Development
 Transport in Porous Media
 Waerme-und Stoffuebertragung

Aircraft Temperature Control Using Heat Pipes

Exterior surfaces on proposed hypersonic vehicles may experience intense stagnation heating rates during the ascent and re-entry portions of their trajectories. The use of liquid metal heat pipes has been considered to reduce the temperature of leading-edge surfaces on the wings and engine cowl. Heat pipes used in this fashion would be subjected to highly variable heating rates and body forces, requiring consideration of working fluid distribution over repeated startups and shutdowns. Boman (1990) at the McDonnell Douglas Aircraft Company tested a Hastelloy X-sodium heat pipe for use on the wing leading edge of an advanced re-entry vehicle. Cao and Faghri (1992a, 1993a) at Wright State University reviewed techniques for hypersonic vehicle cooling and developed a finite-difference numerical model for simulating the transient performance of nose cap and wing leading edge heat pipes. Colwell and Modlin (1992, 1993) at Georgia Tech reported the results of a finite-difference model that was used to compare different methods to cool leading edge surfaces, also see Modlin (1992). These methods included the use of alkali metal heat pipes with surface transpiration or film cooling. Hendrix (1990) also at Georgia Tech, studied the effect of body forces on the capillary, boiling, and entrainment limits of heat pipes. Glass (1990) at the NASA Langley Research Center presented a thermal analysis of a carbon-carbon/refractory-metal heat-pipe-cooled wing leading edge. Martin (1992, 1994) at Los Alamos National Laboratory reported the results of molybdenum-sodium heat pipe tests conducted at simulated Mach 5 thermal boundary conditions.

Heat pipes have also been considered or developed for cooling engine components in conventional aircraft. Gottschlich (1992) at Wright-Patterson Air Force Base described the cooling of gas turbine engine vanes using heat pipes. Ponnappan (1995) at Universal Energy Systems in Dayton, Ohio, presented test results of a stainless steel-water on-axis rotating heat pipe intended to regulate the temperature of electrical machines directly mounted on the main shaft of a gas turbine engine. Silverstein (1994) at CCS Associates reported the use of heat pipes to cool the vanes of gas turbine engines. Yerkes (1990) and (1992) with Wright Laboratory tested artery-heat pipes and thermosyphons for the thermal control of electric motors, compressors, and generators in aircraft experiencing transverse accelerations. Partial depriming of the heat pipe artery, pooling of unconstrained working fluid, and fluid sloshing were observed. Heat pipe repriming under transverse accelerations was demonstrated.

Electronic Cooling Heat Pipes

This section briefly summarizes some applications of heat pipes in the cooling of electronic components. For a discussion of the cooling of computer chips using heat pipes, also refer to the section on micro and miniature heat pipes later in this report. Gernert at Thermacore developed gravity assist heat pipe (1991) and wicked flexible loop heat pipe (1995) cold plates for electronics cooling in aircraft. Gu (1994) at the University of Kentucky reported the thermal performance of wicked flat plate electronics cooling heat pipes charged with FC-70 or FC-72. Noren Products of Menlo Park,

California, manufactures both stock and custom heat pipes for a variety of electronic cooling applications. Des Champs Laboratories, Incorporated, of Natural Bridge Station, Virginia, manufactures standard and custom industrial air-to-air heat pipe heat exchangers for electronic cabinet cooling. North (1993) and Rosenfeld (1994) both at Thermacore discuss some applications of heat pipes to microelectronics cooling.

Heat Pipes In Heat Exchangers And Industrial Processes

Hill (1993) studied supermarket air-conditioning systems equipped with heat pipe heat exchangers. Operation in four different climates was considered. The heat pipe heat exchangers were used to save refrigeration energy by reducing the humidity of the refrigerated spaces. Rosenfeld (1995) at Thermacore discussed the use of heat pipes in "porous media heat exchangers" for the cooling of high heat load optical components.

A number of commercial manufacturers located in the US and Canada produce heat exchangers that use heat pipes. ABB Air Preheater, Incorporated of Wellsville, New York, produces heat pipe heat exchangers used as air preheaters for electric utility boilers, hydrocarbon processing industry furnaces, and gas-to-gas heat exchangers used in waste incinerators. Des Champs Laboratories, Incorporated, of Natural Bridge Station, Virginia, builds standard and custom industrial air-to-air heat pipe heat exchangers for electronic cabinets used in clean rooms, transmitter and telecommunication stations, and computers. Heat pipes in Des Champs heat exchangers are typically charged with a refrigerant and use a knurled-wall construction. Heat Pipe Technology, Incorporated of Alachua, Florida, uses internally finned refrigeration tubes to transport liquid in their manufactured heat pipe heat exchangers for dehumidification and energy recovery. Hudson Products Corporation of Houston, Texas, manufactures modular heat pipe air heaters for energy recovery in hydrocarbon processing plants. Heat pipes built by Hudson Products use water-based working fluids and have a 2-inch outside diameter with externally enhanced heat transfer surfaces. Noren Products, Incorporated of Menlo Park, California, builds small air-to-air heat exchangers. QDT, Limited of Dallas, Texas manufactured air-to-air heat pipe heat exchangers for building energy recovery. QDT heat pipes are slightly inclined to provide gravity assist and have a knurled internal surface for liquid distribution. Working fluids used in these heat pipes include R-22, R-134a, R-123, R-124, naphthalene, and toluene. In August 1994, QDT was bought by Engineered Air of Calgary, Alberta which moved part of the heat pipe manufacturing operation to Canada and retained the QDT trade name. Thermacore, Incorporated, of Lancaster, Pennsylvania, manufactures a line of heat pipe coolers for electronic cabinets.

Heat pipes have also been developed for various industrial processes. Judd (1994) at McMaster University in Hamilton, Ontario designed and tested a heat pipe to cool a milling machine spindle. Later, Judd (1995), investigated the use of heat pipes to regulate the temperature of a carbide cutting tool on an engine lathe. Acrolab, Incorporated in Windsor, Ontario manufactures heat pipes to isothermalize molds and extruders used in the plastics and rubber industries.

Solar Energy Conversion Using Heat Pipes

Reflux solar receivers for dish-Stirling power generation systems are being developed by several companies and laboratories in the United States. Andracka (1992) and Adkins (1993) both of Sandia National Laboratories-Albuquerque reported the status of a US Department of Energy-sponsored program to use an alkali metal heat-pipe solar receiver to transfer thermal energy from the focus of a concentrator to the heater-tubes of a dish-Stirling system. In 1991, Dynatherm, Incorporated of Cockeysville, Maryland developed a prototype screen-wick stainless steel-sodium reflux heat pipe receiver for this program. Hartenstine (1994) at Thermacore discussed the potential of a hybrid solar and gas-fired heat pipe receiver for a Cummins 7.5 kW_e Stirling engine/generator system. Hogan (1994) at Sandia National Laboratories-Albuquerque reported the development of a numerical model to predict thermal performance of pool-boiler and heat-pipe reflux receivers. Baker (1990) at the NASA Lewis Research Center described a heat pipe solar dynamic space power receiver. Redundant heat pipe arrays were considered in this proposed design to enhance receiver reliability.

Spacecraft Heat Pipe Development

Heat pipe development for spacecraft thermal control continues to be an especially active area in the US. In a recently published book Gilmore (1994) discusses the application of heat pipe and capillary pumped loops to spacecraft thermal control. Swanson (1992) at NASA Goddard Space Flight Center summarized some current and potential uses of heat pipes in spacecraft.

During the 1990-1995 period a number of heat pipe experiments were conducted aboard US Space Shuttle missions. Prototype sections of the Space Station Heat Pipe Advanced Radiator Element-II (SHARE-II) were tested on the Space Shuttle Atlantis during STS-37 in April 1991. The SHARE-II radiator used grooved ammonia heat pipes developed by Lockheed and was intended for use on the Space Station Freedom. This test was a continuation of a full-scale heat pipe experiment carried in the payload bay of STS-29 in 1989. The 1989 experiment revealed a blockage in the radiator's T-shaped vapor manifold. The STS-37 experiment included two sub-scale test articles: a redesigned Y-shaped manifold section and an apparatus to test the design of a screen used to reduce bubble formation in the heat pipe wick structure.

A redesigned SHARE II radiator panel later flew on Atlantis (STS-43) in August 1991 with heat pipe radiator elements built by both Lockheed and Grumman. The design of the Lockheed radiator element was described by Ambrose (1992). Brown (1991) reported on the design of the Grumman radiator element. Ochterbeck (1995b) used heat pipe test results taken during STS-43 to compare with a model of the priming and rewetting characteristics of two external artery heat pipes.

An experiment to study the micro gravity effects on the priming of heat pipes was conducted aboard Columbia (STS-52) in October 1992. A total of 14 heat pipes were

tested: eight with axial grooves and six with fibrous wicks. Some of the heat pipes were copper-water and the others were aluminum-Freon 113. Data from these tests were used to modify and validate the NASA Groove Analysis Program (GAP) heat pipe code.

A heat pipe flight test was on a Hitchhiker canister aboard the Space Shuttle Discovery (STS-53) in December 1992. The canister housed two oxygen heat pipe designs: one made by TRW in Torrance, California, the other by Hughes Aircraft Company in Huntington Beach, California. These heat pipes, cooled by five Stirling-cycle cryocoolers, were developed to demonstrate heat rejection techniques for spacecraft infrared sensors. The results of this test were summarized by Brennan (1993).

McDonald (1994) at Martin Marietta described a pair of copper-acetone heat pipes built by Thermacore. These heat pipes were designed to transfer heat from a refrigerated space to the cold finger of a Stirling-cycle cooler. This cooler was flown aboard SpaceHab 2 on STS-60 in February 1994. A thermal performance test of freon charged heat pipes under micro gravity conditions was manifested on Atlantis (STS-66) in November 1994. Ten different axially grooved aluminum-freon heat pipes were launched. These heat pipes were tested to determine heat transport capacity and conductance with different freon charges using uniform and asymmetric heat loads and single and multiple heated zones. Data were also taken to find the rewicking points for undercharged pipes and to determine the effect of body forces on thermal performance. The results of these tests were to be used to further modify the NASA GAP heat pipe code.

An oxygen heat pipe built by Hughes Aircraft Company flew on Discovery (STS-63) in February 1995. This diode heat pipe thermally coupled a Stirling-cycle cryocooler to a thermal energy storage device. In-flight tests were conducted to characterize heat pipe startup performance and steady state behavior.

An OAO/Swales developed capillary pumped loop flew as a Hitchhiker payload aboard Endeavor (STS-69) in September 1995. A similar ammonia-charged capillary pumped loop failed in startup when it flew on Discovery (STS-60) in February 1994. The STS-69 loop design was modified from its predecessor and was successfully tested. A full scale capillary pump loop design, based on these tests, was the baseline thermal control system for the Earth Observing System (EOS AM-1) program.

Woloshun (1993) described the design, fabrication, and ground test at Los Alamos National Laboratory of three stainless steel-potassium heat pipes: one with a homogeneous screen wick, one with an arterial wick, and the last with an annular gap wick. This experiment, sponsored by the US Air Force Phillips Laboratory, flew aboard STS-77 in May 1996, becoming the first American-built liquid metal heat pipes to operate in micro gravity conditions.

The SP-100 space nuclear reactor program provided a much-needed impetus for the development of alkali metal heat pipes during the 1980s and early 1990s. The baseline SP-100 design gradually evolved into a pumped, lithium cooled reactor with thermoelectric conversion by way of a potassium heat pipe radiator. El-Genk (1990) at the University of New Mexico numerically simulated the response of a SP-100 heat pipe

radiator design to an externally applied thermal exposure. Sena (1990) at Los Alamos National Laboratory reported the results of life tests on eight niobium-potassium and three titanium-potassium heat pipes operating under simulated SP-100 conditions for up to 14,000 hours. Rovang (1994) at Rockwell reported progress in the development of a lightweight carbon-carbon composite-potassium heat pipe radiator element for the NASA Lewis Research Center. A vapor deposited layer of niobium over a thin rhenium interlayer coating protects the carbon-carbon radiator structure from attack by the 875-K potassium working fluid, for related work see Rosenfeld (1991). Hainley (1991) describes a heat pipe space radiator code that was written for the NASA Lewis Research Center. This code designs and analyzes radiators that transfer heat from a pumped fluid loop to the evaporator sections of heat pipes. A design methodology for heat pipe space radiators was described by Lund (1993). A number of alternative reactor energy conversion schemes were considered in addition to the SP-100 baseline. Schmitz (1993) at the NASA Lewis Research Center discussed the design of heat exchangers to couple the SP-100 primary lithium loop to a Stirling cycle power converter. Ernst (1992) at Thermacore investigated the use of sulfur-iodine as a heat pipe working fluid for free-piston Stirling cycle heat pipe radiator applications in the 475 K to 700 K temperature range. Baker (1992) developed relations for anisotropic heat conduction in a heat pipe space radiator fin and used them to arrive at minimum mass radiator designs.

Since the demise of the SP-100 program in the early 1990s several new reactor designs have been proposed. Ranken (1991) at Los Alamos National Laboratory presented the results of studies on a thermionic reactor concept that uses a combined beryllium and zirconium hydride moderator that allows heat pipe cooling of a compact thermionic fuel element. This design, dubbed "Moderated Heat Pipe Thermionic Reactor" (MOHTR) would be useful for space reactors in the tens of kilowatts electrical power regime. A test of a MOHTR potassium heat pipe module was described by Merrigan (1992). Houts (1995) also at Los Alamos National Laboratory described a spacecraft reactor system using heat pipes which could produce propulsion as well as 5 to 10 kW_e. Recent space-power-related heat pipe technology was reviewed by Merrigan (1994), also see Eastman (1990).

Heat Pipe Modeling

Over the last 10 years a host of computationally inclined heat pipe investigators in the US have been busy modeling heat pipe transient operation. The difficulty of transient heat pipe modeling can be immense, especially if a simulation of the frozen startup problem is attempted. Important mechanisms related to transient heat pipe operation include: the transition from free molecule to continuum flow in the vapor space, the migration of the melt front in capillary structures, mass transfer between the liquid and vapor regions, compressibility effects and shock formation in the vapor flow, and the possibility of externally imposed body forces on the working fluid in its liquid phase. Performance limiting mechanisms during power transitions in recently proposed heat pipe systems include evaporator entrainment, freeze out of the working fluid inventory in the condenser, evaporator capillary limits, and nucleate boiling departure in the evaporator.

Bowman (1991), (1992) at the Air Force Institute of Technology developed a one dimensional, quasi-steady solution for gas flow that is compressible in time and spatially incompressible. This solution was used to model flow in a heat pipe vapor space. Bowman (1994) presented two implicit solution methods for modeling the gas flow in a heat pipe vapor space. Issacci and Catton (1991) at the University of California-Los Angeles developed a model of a rectangularly-shaped heat pipe vapor space during startup beginning from the liquid state. They considered compressibility effects including a treatment of the shock front. Discretization of the convective terms was calculated with a center-difference scheme and a nonlinear filtering technique was used to handle shocks. Multiple wave reflections were reported in the evaporator and adiabatic regions.

Ambrose (1991) at the University of Kentucky modeled transient liquid flow in heat pipe wicks. Chow (1990) also at the University of Kentucky used a 3-dimensional, alternating direction implicit method in a transient finite-difference model of a high-temperature, axially grooved heat pipe coupled to a thermal energy storage system. Colwell and Modlin (1992) and (1993) at the Georgia Institute of Technology developed a finite-difference based post-startup transient model of a liquid metal heat pipe for hypersonic vehicle cooling.

Faghri and others at Wright State University (by 1995 Faghri had moved to the University of Connecticut) reported the results of a series of heat pipe analysis models. Cao and Faghri (1990) developed a transient two-dimensional heat pipe model that calculates a compressible vapor flow solution for application to a high temperature heat pipe experiencing pulsed heat loads. Cao (1991) presented a model of a heat pipe with nonuniform heat distributions using a body-fitted grid system with a three-dimensional wall and wick model coupled to a transient compressible quasi-one-dimensional vapor flow model. A model of frozen startup behavior of a low-temperature heat pipe was presented by Faghri (1992a). Later work by Cao (1993b) reported the development of models considering high temperature heat pipe frozen startup with a moving sharp-front hot zone, capillary and sonic limits in the wick, continuum flow (which was modeled using the Navier-Stokes equation for compressible flow) and free molecule flow (which was simulated using a self-diffusion model), also see Cao (1993c).

Hall (1990) at North Carolina State (and later at Los Alamos National Laboratory) developed a model of heat pipe transient behavior starting with the working fluid in the frozen state. This model was later modified, Hall (1994). Hall used an implicit first-order accurate scheme that is one dimensional and compressible in the vapor space. Accommodation coefficients in the condenser and evaporator regions were adjusted during code validation. Code predictions were compared with data reported by Merrigan (1985).

Jang (1990), (1991) outlined discrete phases of frozen heat pipe startup and developed a transient model that was two-dimensional in the wall and the wick. This solution was coupled to a one-dimensional vapor flow model at appreciable vapor pressure. Mass transfer between the liquid and vapor regions was ignored at low vapor pressure. Jang used this model to study the effect of the boundary conditions on frozen state startup.

Tournier and El-Genk (1992) at the University of New Mexico developed a two-dimensional, heat pipe transient analysis model that simulates the operation of fully-thawed liquid-metal- and non-liquid-metal- heat pipes. This model was subsequently improved Tournier (1994a), (1994b) and was benchmarked against experimental data for inclined water heat pipes Huang (1993), El-Genk (1993), and El-Genk (1995). A later version of this code was used to simulate the startup of a radiatively cooled water heat pipe from the frozen state Tournier (1995). A review of both steady state and transient heat pipe codes was given by Gurule (1992). A later review of transient heat pipe modeling techniques was given by Faghri (1994a). Faghri cited work by Bowman, Cao, Costello, Hall, and Jang.

Several studies also examined heat pipes behavior using analytical (non-CFD) techniques. Cao (1992b) at Wright State University developed a closed-form solution of heat pipe startup using a flat front assumption. Faghri (1994b) described a transient lumped-parameter heat pipe analysis that considered different evaporator and condenser boundary conditions. Dalmas (1993) at the Federal University of Santa Catarina in Sao Paulo, Brazil used a frequency response technique to analyze unsteady, two-dimensional heat conduction effects in the wall and the wick of various heat pipe designs. Tower (1992b) and others at NASA Lewis Research Center developed a steady state heat pipe code that runs on a personal computer or as a subroutine in a mainframe computer radiator code. The Lewis code can model heat pipes with multiple evaporators, condensers, and adiabatic sections.

Heat Pipe Performance Limits

A number of papers and articles dealt, to varying degrees, with performance limits in heat pipes and thermosyphons. Charlton (1994) at the Air Force Institute of Technology experimentally studied the effect of transverse vibration on the heat pipe capillary limit. Huber (1993) at the Air Force Institute of Technology observed a small decrease in the capillary limit of a screen-wicked copper-water heat pipe induced by longitudinal vibrations. In an experimental study of heat pipe startup, Jang (1995) at Sverdrup, observed evaporator dryout with heat transport rates smaller than the steady state capillary limit. Duncan (1995) at Texas A&M included a capillary limit calculation in a steady state model for a micro heat pipe with a triangular cross section. Hendrix (1990) at Georgia Tech studied the effect of body forces on liquid movement within a heat pipe and the resulting effect on the capillary, boiling, and entrainment limits. Keddy (1994) at Los Alamos National Laboratory modeled liquid metal heat pipes operating at low power throughputs where evaporator dryout could occur because of inventory migration to a frozen region of the heat pipe. McCreery (1994) at the Idaho National Engineering Laboratory visually observed vapor formation and boiling in a heat pipe wick structure. Ochterbeck (1995a) at Texas A&M visually studied a transient "freezing blowby effect" in a heat pipe evaporator undergoing startup. In this effect, a liquid slug is blown out of the wick in the evaporator section and toward the condenser, temporarily increasing heat transport capacity. The resulting liquid inventory loss may cause momentary or permanent evaporator dryout. Several studies at Texas A&M investigated entrainment in

heat pipes and thermosyphons. Kihm (1994) used dimensionless analysis to correlate experimental data measuring the entrainment onset velocity from a simulated saturated wick surface, also see Kim (1994) and Kim (1995). Peterson (1991a) considered entrainment in both heat pipes and thermosyphons. In a later article, Peterson (1993b) reviewed several rotating and revolving heat pipe studies which included some information on performance limits. Prenger (1993) at Los Alamos National Laboratory measured performance limits in oxygen and hydrogen heat pipes with a screen-wick, inverted-artery capillary structure. Richter (1994) at the Jet Propulsion Laboratory, departing from the usual, considered heat pipe performance limits from a thermodynamic viewpoint. Schmalhofer (1993) at Wright State University experimentally measured the capillary limit in a copper-water heat pipe. Swanson (1995) at Texas A&M developed relationships for the "thermocapillary" heat-transport limit in a micro heat pipe. Vafai (1995) at Ohio State University analytically studied the performance limits of a disk-shaped, asymmetric heat pipe using steady state, incompressible vapor and liquid flow relations.

Materials Issues Related to Heat Pipes

Some heat pipes material-related issues investigated during the 1990-1995 period include liquid-solid wetting and surface phenomena; fluid-container compatibility; wick development; and protection of heat pipes from the surrounding environment. Wayner, DasGupta, and others at Rensselaer Polytechnical Institute are engaged in fundamental studies of solid-liquid-vapor interactions involving evaporation and condensation. For recent examples of their prolific work see DasGupta (1995) and Wayner (1994). Peng (1993) at Texas A&M examined the rewetting characteristics of capillary-induced liquid flow in microfin tubes. Tower (1992a) at Sverdrup conducted a simple analysis of nickel-superalloy dissolution, transport, and deposition in a sodium-filled heat pipe.

Ambrose (1993) at Lockheed conducted a 600-day life test on aluminum-ammonia heat pipes that were cleaned with newly used water-based solvents. Gas generation rates for the pipes cleaned with the water-based solvents were compared with results for heat pipes cleaned with TCA and Freon 113. Anderson (1993) at Thermacore considered the use of a sodium-potassium eutectic as a heat pipe working fluid. Tests with this working fluid revealed large temperature nonuniformity in the heated zone from preferential evaporation of the potassium component. Grzyll (1991) at Mainstream Engineering investigated the use of biphenyl as an intermediate temperature working fluid. The thermal stability of biphenyl was believed to be good at 623 K and it was observed to have better thermal transport properties than cesium. Rovang (1994) at Rockwell tested a potassium-charged heat pipe for 11 hours. This pipe was in good condition after eight thermal cycles from ambient to 700 K. Sena (1990) at Los Alamos National Laboratory tested nine niobium-potassium heat pipes with impurity levels being evaluated in the heat pipe materials before and after testing. The heat pipes were operated between 800 and 900 K, with radial heat fluxes of 13.8 to 30 W/cm² for up to 13,000 hours.

Adkins (1995) at Sandia National Laboratories-Albuquerque used precision metal felts for wicks in sodium heat pipes for a solar power converter. The felt consisted of micron

diameter wires with a wool-like consistency with greater than 90% porosity, effective pore radii from 40 to 120 nm, and permeability from 30 to 300 nm².

The use of ceramic fabric materials has been proposed for the protection of spacecraft heat pipe radiators from micrometeoroids and space debris. Several studies were conducted to characterize the properties of these fabrics. Antoniuk (1991) at Pacific Northwest National Laboratory reported the development and emittance testing of titanium-water heat pipes covered with various ceramic fabrics. The use of supplemental emittance-enhancing coatings was suggested to increase the emittance of the fabric surface from 0.5 to 0.9. Marks (1991) at Oregon State University tested ceramic fiber cloth as wicking material for heat pipes, also see Klein (1993). Merrigan (1991) at Los Alamos National Laboratory tested aluminaborosilicate-covered stainless steel-sodium heat pipes for use in high temperature radiators. The tests indicated radiation heat rejection rates from the fabric covered surface was strongly affected by the emittance of the underlying metal substrate.

Capillary Pumped Loops

This section briefly covers the developing field of capillary pumped loops and loop heat pipes. During the 1990-1995 period most published information in this area is found in conference papers rather than journal articles. Antoniuk (1995) described an unsuccessful test of a capillary pumped loop aboard the US Space Shuttle. Startup failure under microgravity conditions was attributed to liquid blockage in the evaporator vapor spaces before heat was applied to the evaporator. A "capillary vapor flow valve" inserted in the vapor flow path downstream of the evaporator vapor manifold was proposed to stop vapor flow toward the condenser until the evaporator vapor spaces were cleared of liquid. Cao (1994a) at Wright State developed a model for a flat-plate type evaporator in a capillary pumped loop. Cao considered liquid flow and heat transfer in the wick, 3-dimensional vapor flow in the groove, and coupled the liquid and vapor solutions with an interfacial mass flux relation. Shyy (1994) at the University of Florida modeled axisymmetric two-phase transient flow behavior of a capillary-pumped-loop reservoir. Gravity forces, applied power, and reservoir orientation were varied and several convection modes were identified. Dickey (1994) at Texas A&M tested a capillary pumped loop at various power inputs and tilt angles. A computer model of the loop was developed which was compared to experimental results. Ernst (1994) at Thermacore described the operating principles of a close-cousin to the capillary pumped loop: the self-priming loop heat pipe. Ernst cited data from hardware tests and described recent developments and applications of the technology, also see Gernert (1995). A survey of capillary pumped loop development was given by Ku (1994) of the NASA Goddard Space Flight Center. Ku traced the development of capillary pumped loop technology from the late 1970s and cited numerous AIAA, SAE, and NASA conference papers from the 1980s and early 1990s that formed the backbone of the documented capillary pumped loop literature.

Gas Loaded and Variable Conductance Heat Pipes

There has been surprisingly little reported on variable conductance heat pipe development during the 1990-1995 period. Grote (1992) at McDonnell Douglas gave results of a variable conductance heat pipe experiment that was conducted on the Long Duration Exposure Facility in the mid-1980s but retrieved in the early 1990s. Gillies (1994) at the NASA Marshall Space Flight Center discussed the use of variable conductance heat pipe technology in a moving gradient furnace for spacecraft applications. Several articles have either presented models of gas loaded heat pipe operation or examined their use to enhance heat pipe operating characteristics. Harley (1994b) at Wright State University reported the development of a transient two dimensional model of a gas loaded heat pipe. Ochterbeck (1993) at Texas A&M looked at the freeze and thaw characteristics of a copper-water heat pipe with a rectangular cross section to find the effect of variations in the amount of noncondensable gases present. Peterson (1990) examined mixed double-diffusive convection in gas-loaded heat pipes. Ponnappan (1990), (1994) used inert gas to aid in the frozen state startup of an argon-loaded sodium heat pipe. Ponnappan developed a two-dimensional, quasi-steady state, binary vapor-gas diffusion model and compared its results to the experimental data. Shaubach (1992) at Thermacore examined the effect of noncondensable gas on the performance of an alkali metal heat pipe with an artery wick structure. Artery depriming was postulated to occur if noncondensable gas comes out of solution in sufficient quantity to block artery liquid return to the evaporator. Frozen startup test data with a gas loaded stainless steel-sodium artery heat pipe were presented in support of this postulate.

Micro and Miniature Heat Pipes

Micro heat pipes, as first proposed by Cotter (1984), are defined to be "so small that the mean curvature of the liquid-vapor interface is necessarily comparable in magnitude to the reciprocal of the hydraulic radius of the total flow channel." Micro heat pipe should be distinguished from miniature heat pipes which have a larger hydraulic radius to liquid-vapor interface curvature ratio. Advances in integrated circuit technology have spurred miniature and micro heat pipe development. During the last twenty years, component density on integrated circuits has grown from about six thousand transistors on the Intel 8080 microprocessor to over five million transistors on a similar-sized Intel P6 microprocessor. Power and component densities on these integrated circuits correlate and have required the development of innovative cooling methods.

Both micro and miniature heat pipes appear promising for use in microelectronics cooling. Micro heat pipes which could be embedded directly onto the silicon substrate of an integrated circuit have been investigated in several studies conducted at Texas A&M: Mallik (1992), (1995c), and Peterson (1993a). Babin (1990) also at Texas A&M reported experimental data taken on several water-charged micro heat pipes with a cross sectional dimension of about one millimeter. Babin also developed a steady-state micro heat pipe model to quantify heat transport capacity. Adkins (1994) at Sandia National Laboratories-Albuquerque discussed the use of a "heat-pipe heat spreader" embedded in a

silicon substrate as an alternative to the conductive cooling of integrated circuits using diamond films. Longtin (1994) at the University of California-Berkeley developed a one-dimensional steady state model of the evaporator and adiabatic sections of a micro heat pipe which calculated working fluid pressure, velocity, and film thickness along the length of the pipe. Technical issues related to micro heat pipes investigated during this period include: liquid distribution and charge optimization Duncan (1995), Khrustalev (1994), Mallik (1995a); interfacial thermodynamics in micro heat pipe capillary structures Swanson (1993), Swanson (1995); and micro heat pipe transient behavior Mallik (1995b), Wu (1991a), Wu (1991b). Two reviews of micro heat pipe literature were conducted during the 1990-1995 period: one by Peterson (1992) and another by Cao (1994b).

Miniature heat pipes attached directly to ceramic chip carrier casings have also been considered. A recent application of miniature heat pipe technology in the US was the development by Thermacore (starting in 1994) of heat pipes to cool the Pentium microprocessors used in notebook computers.

Other proposed applications of micro or miniature heat pipes discussed by American authors during this period include: the removal of heat from hypersonic aircraft leading edge surfaces Camarda (1991), thermal conductivity enhancement in high temperature spacecraft radiator fins Badran (1993), and the non-surgical treatment of cancerous tissue through hyper- or hypothermia (Fletcher and Peterson, 1993, US Patent 5,190,539).

Rotating Heat Pipes And Thermosyphons

Several investigations have been conducted during the 1990-1995 period on rotating heat pipes and thermosyphons. Salinas and Marto (1991) at the Naval Postgraduate School developed a two-dimensional, steady-state numerical model of conjugate condensation and wall heat conduction in an internally-finned, coaxial, rotating heat pipe charged with Freon or water. Faghri (1992b), (1993a) at Wright State University reported on a numerical model with similar functionality and conducted a parametric study varying radial Reynolds number and rotational speed. Their results indicated a non-uniform radial pressure distribution and a vapor flow reversal near the heat pipe centerline at high rotational speed. Harley (1995), also at Wright State University, developed a transient numerical simulation of rotating heat pipes. This simulation considered the coupling of the condensate film to the vapor space as well as unsteady heat conduction in the heat pipe wall. A Nusselt-type condensation analysis was used to analyze the effects of the vapor pressure drop and the interfacial shear stress. Ponnappan (1995) discussed a stainless steel-water on-axis rotating heat pipe. Yerkes (1990) reviewed the development and potential benefits of rotating two-phase thermosyphons for aircraft thermal management applications. Peterson (1993b) reviewed and summarized analytical and experimental investigations conducted on three different types of heat pipes: rotating heat pipes with an internal taper, rotating heat pipes without an internal taper, and revolving heat pipes. The effect of variations in the taper angle, liquid charge, rotational position, and the quantity of noncondensable gases were discussed in Peterson's review.

Thermosyphon Heat Pipes

The word "thermosyphon" is used to describe both single-phase and evaporative gravity-assist heat transport devices. For an example of a single-phase thermosyphon see Polentini's article describing *natural convection* heat transfer from an array of flush-mounted, discrete heat sources, Polentini (1993). Several thermosyphon studies have been conducted North of the US-Canadian border. Lock at the University of Alberta investigated both single phase (1993c), (1993e) and evaporative thermosyphons. Issues examined related to evaporative thermosyphons included the influence of evaporator and condenser inclination on the performance of a right-angled thermosyphon Lock (1993d), also see Lock (1993b); and the role of the Bond, Froude, Weber and Kutateladze numbers on the flooding limit in the evaporator, Lock (1993a). Haynes (1992) at the University of Alaska reported the performance of a thermosyphon with a 37-meter long horizontal evaporator to be used for permafrost stabilization at a radar site power plant building in Gakona, Alaska.

Thermosyphon-related studies have been also reported by several US investigators in the lower 48 states. Fox (1993) at the University of California-Berkeley looked at heat and mass transfer inside thermosyphons using binary hexane-pentane and hexane-R-11 mixtures. Heat transport in these thermosyphons was observed to be a function of the mixture ratios between the two components, the power throughput, as well as the ratio of the molecular weights of the components. Harley (1994a) developed a transient two-dimensional thermosyphon model that considers conjugate heat transfer through the wall and the falling condensate film and uses a quasi-steady Nusselt-type solution for the liquid film. Peterson at Texas A&M investigated the entrainment limit in thermosyphons (1991a) and flow instability in gas-loaded reflux thermosyphons (1991b). Yerkes (1990) looked at the use of rotating thermosyphons for aircraft thermal control applications. Zuo (1994), (1995) at the University of Central Florida reported the development of a "first principle" steady state evaporative thermosyphon model. Liquid-film momentum convection and axial normal stresses were considered as well as a variety of thermal boundary conditions.

Low Temperature And Cryogenic Heat Pipes

Ambrose (1994) at Lockheed tested an axially-grooved fixed-conductance heat pipe charged with propane. This heat pipe was operated around 200 K. Steady state analytical heat transport predictions were verified and an optimum propane charge quantity was established. Beam (1992) at Wright Laboratory and later Brennan (1993) at the NASA Goddard Space Flight Center described an in-flight test of two axially grooved oxygen heat pipes aboard the shuttle Discovery in December 1992. The startup of the oxygen heat pipes on-orbit was observed to be slower than in ground tests. Each pipe was started three times and heat transport data was collected between 60 K and 140 K. McIntosh (1993) also at the NASA Goddard Space Flight Center reported test results from two 1970s vintage ethane heat pipes that flew aboard the Long Duration Exposure Facility. One was an axially-grooved, fixed-conductance heat pipe with an aluminum wall.

The other was an axially-grooved, stainless steel heat pipe diode. During the mid-1980s these pipes were operated continuously on-orbit for 390 days at temperatures below 200 K. Brown (1992) at Wright Laboratory tested the response of an axially grooved aluminum-oxygen heat pipe to various tilt-angles. This pipe was started from the supercritical state and its transient response during heat loads leading to evaporator dryout was characterized. Prenger (1993) at Los Alamos National Laboratory tested two screen-wick inverted-artery heat pipes operating as a thermal switch for a spacecraft sensor cooling application. One pipe was charged with oxygen and the other with hydrogen. The performance limits for these heat pipes were tested. Startup from the frozen and supercritical states was also demonstrated. Hamilton (1992), (1993) at Synerdyne Corporation developed a thermoelectrically-cooled ammonia heat pipe probe for cryotherapy and cryosurgery. The probe tip could be kept below 240 K while carrying a 10 W cooling load.

Alkali Metal Heat Pipes (Experimental)

Adkins (1992) at Sandia National Laboratories-Albuquerque described the development and testing of a sodium heat-pipe heat exchanger that was designed to transfer thermal energy from hot combustion gases to the heater tubes of a Stirling engine. An update of this program was presented by Andraka (1992). Anderson (1993) at Thermacore proposed the use of a sodium-potassium eutectic mixture as a heat pipe working fluid to eliminate potential frozen startup problems in liquid metal heat pipes. Jang (1995) tested potassium heat pipe startup at various heating rates. He also observed that after the working fluid in the condenser was completely melted, the evaporator could be rewetted without external aid. Merrigan (1991) at Los Alamos National Laboratory tested the influence of aluminoborosilicate fabric coverings on radiation heat rejection rates from stainless steel-sodium heat pipes. Nguyen (1991) at the University of Kentucky tested the response of a screen wick, sodium heat pipe to pulse heat loads applied to the condenser section. Ponnappan (1994) described tests of a sodium-charged artery heat pipe to measure its startup behavior in both vacuum and gas-filled modes. Sena (1993) at Los Alamos National Laboratory described tests of two annular niobium-potassium heat pipes: one with a multilayer etched foil wick, the other with a composite screen wick. Trujillo (1990) also at Los Alamos performed tests on a deployable, membrane heat pipe radiator element using stainless steel foil as a containment material and a sodium working fluid. Passive deployment of this element at 800 K was demonstrated as well as steady state operation at 1000 K. Woloshun (1990) again at Los Alamos presented boiling limit test data for a niobium-potassium heat pipe operating at 1000 K. Boiling was observed at a radial heat flux in the evaporator region of 147 W/cm².

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